NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 1

Kellie Ann Beall, Editor

June 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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Modeling of Heating Mechanism and Thermal Response of Structural Components Exposed to Localized Fires: A new application of diffusion flame modeling to fire safety engineering

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ABSTRACT

A framework for investigation of the feasibility of unprotected structure from the firesafety point of view is discussed. Experimental heat transfer and temperature correlations for flat ceiling and a beam beneath a flat ceiling exposed to localized fire source are shown. The experimental results suggest feasible range of unprotected structures from the fire safety point of view and basic information for the fire safety design of unprotected structures.
Key Words: localizedfire, unprotected structure, heatflux, flame length.

SCOPE AND RESEARCH FRAMEWORK

There is considerable potential need for the development of unprotected or weakly-protected fire-safe structures, although current fire regulation in most of industrialized counties requires that load bearing structures be protected against fire with thermal insulation[1,2]. However, on-site installation of thermal insulation to structural members is a typical time- and labor-consuming process in construction and its maintenance is often difficult for traffic, seismic or other vibration or for due generation especially in humid climate.

The primary parameter determining the performance of thermal insulation is the severity of the design fire. In many countries, fire resistance tests assume exposure of structural components to a fully developed fire[1,2]. However, a building fire may remain localized if either the compartment or its opening is enough large. Atrium can be a typical built environment large enough to be exempt from a full involvement by fire. For external structural members, fire of adjacent buildings and flame projection should be the only heating source, and heating by such sources is believed to be weaker than fully developed room fires[3,4]. Also, parking buildings and such traffic facilities as railway stations are typical occupancies in which the nature and amount of fire load can be easily limited within a predictable range [2,5,6]. Metal structure has a relative advantage in the simplicity of on-site construction, the lightness and the easiness in future renovation in comparison with masonry or reinforced concrete structures; it is the main reason why metal structures are preferred for traffic facilities and offshore buildings. It is also important that recent efforts for evaluating heat release from burning furnishings are making it possible to predict and control heat release from building contents in fire [5,7]. If a load bearing member is heated only locally in fire, it is believed not only that the heating condition of the member become less significant than in a fully-developed fire but also that conduction loss through the member itself contribute to keep the exposed part cooler. The second benefit of the localized fire is especially pronounced for metal structures since the thermal conductivity of metal is far larger than that of other major structural materials. However, although estimation of the heating condition in fire is a key for the fire safety design of unprotected structures, only few works have been conducted on the modeling of the heating condition by a localized fire and on the analysis of thermal and mechanical response of load bearing components to such fires. Quantification of heating condition of load bearing components by fire is also believed to be useful for fire safety design of bare wooden structures using char layer due to fire exposure as the protection layer.

Prediction of the heating condition due to a localized fire, on the other hand, has been a major problem in the field of active fire protection systems and fire growth modeling. Heating of a ceiling by a localized fire is the dominant problem in evaluating the activation of fire detectors and automatic sprinklers [9-14], and incident heat flux to the interior or exterior lining finish is the key condition for the evaluation of ignitability and flame spread in fire[14-18]. There are numbers of measurement and modeling of the heating mechanism by a localized fire with these subjects as the primary interest, which however deal generally with relatively low heat flux range. Once the heating condition of a load bearing component is modeled in engineering manner, its temperature and mechanical behavior could be calculated numerically with the heat flux distribution as the input. Conventional fire safety design guides for steel structures[1,2,4] do not seem to incorporate such advancement in fire modeling and measurement. Figure 1 is a summary of the diagram necessary for the development of the whole procedure to assess fire safety of structure exposed to localized fires. Detail of this study is reported elsewhere[19~22].

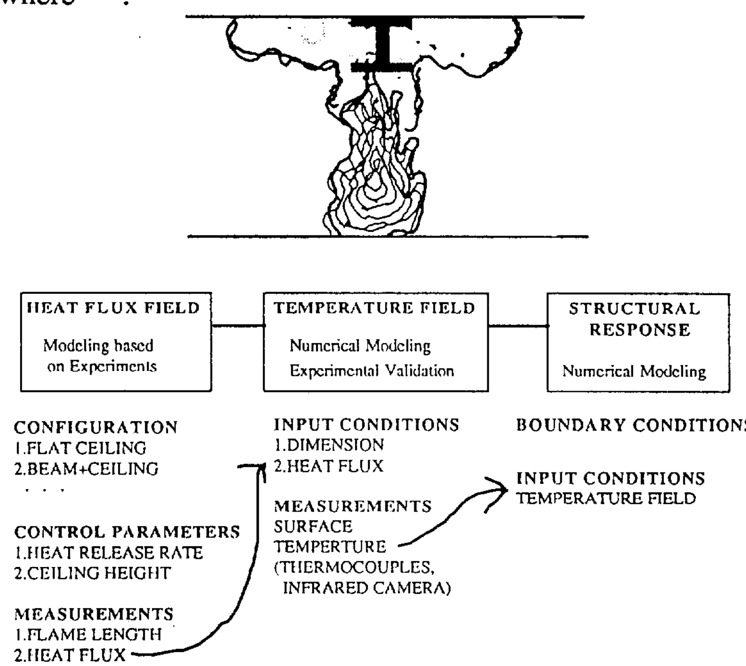


Figure 1 Research Framework

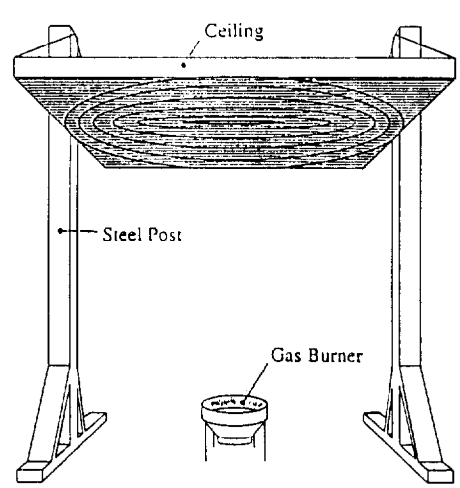


Figure 2 Experimental Setup(Flat Ceiling)

FLAT CEILING EXPOSED TO A LOCALIZED FIRE SOURCE

Heat flux measurement was conducted on an unconfined flat ceiling above an isolated fire source as one of the most basic configurations. Figure 2 is the experimental set up for the flat ceiling above a porous burner. The 1.82 m square ceiling consists of two layers of 12mm mineral-fiber reinforced cement(Perlite) boards and is hung from two steel posts. Height of the ceiling was adjusted by lifting the ceiling along the post. 0.30m and 0.50m diameter round and a 1.0m square porous propane burners were used as the fire source. Intensity of the fire source and the height between the burner surface and the ceiling were changeable. Complete combustion was assumed for the reported values of heat output. Heat flux to the ceiling surface was monitored with 12.5mm diameter Schmidt-Boelter heat flux gages. Temperature of surface and backsurface of the ceiling was measured with 0.2mm K-type thermocouples at various radial distances from the stagnation point to validate numerical models to predict temperature field from heat flux data. Any correction does not have been made on the heat flux data for the difference of the temperature between the sensor and the surface of the specimen. Previous experiments[23] suggest that the heat flux to the specimen surface could be estimated practically within relatively small error by taking $h(T_s - T_g)$ from the heat flux output within the range of heat flux reported in this paper.

Heat Flux at the Stagnation Point

Figure 3 summarizes the dependence of heat flux at the stagnation point on the heat release rate and the ceiling height measured from the burner surface. L_f is the height of unconfined flametips calculated from heat output using

$$L_f = 3.5\, Q^{*n} \cdot D \qquad (1)$$

where n=2/5 for Q*>1.0 and n=2/3 for Q*<1.0 [24,25]. There is significant increase of heat flux at the stagnation point between $L_f/H=1.0$ and $L_f/H=2.5$ until qs" approaches the plateau at qs" ≒ 80～120 kW/m^2. This significant change in the stagnation point heat flux is believed to reflect the vertical oscillation of the flame beneath the ceiling, since the height of solid flame, the main part of the flame as radiation source, is approximately half the L_f [26].

In the transient domain, $1<L_f/H<2.5$, there is clear tendency that ,for a given L_f/H, qs" become larger as the fire source become smaller. This scattering reminds us of the typical systematic scattering of the axial temperature for a buoyant plume around the theoretical $\theta_m \propto z^{-5/3}$ line, which can be practically corrected to the point source theory using the concept of virtual source. Result of the coordination using the virtual source is summarized in Figure 4, in which the qs" − $L_f/(H+z')$ curve for each combination of D and H is almost parallel with large H/Ds in the bottom and small H/Ds in the top. This order probably represents the order of irradiance from the column of the flame beneath the ceiling, whose proportion is believed to be dependent on H/D. The plateau heat flux for approximately $L_f/H>2.5$ is apparently an increasing function of heat release rate as summarized in Figure 5. Interestingly, the Q-dependence of qs" at the plateau is very close to that for the wall heat flux from solid flame from a pool fire against the wall [24].

Horizontal Flame Length Beneath Ceiling and Radial Heat Flux Distribution

For many configurations, relative location of the surface to flame is considered the primary condition controlling the surface flame heat transfer. In order to derive flame length correlations, average of the horizontal distance of the flametips from the stagnation point, L_H, was obtained from videotape. L_H was correlated against the dimensionless heat release rate,Q_{DH}^*, defined as

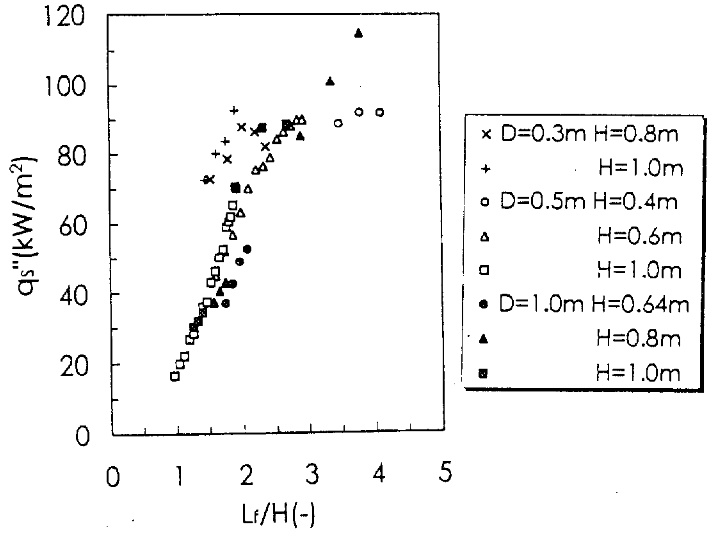


Figure 3 Stagnation Point
Heat Flux vs. Lf/H

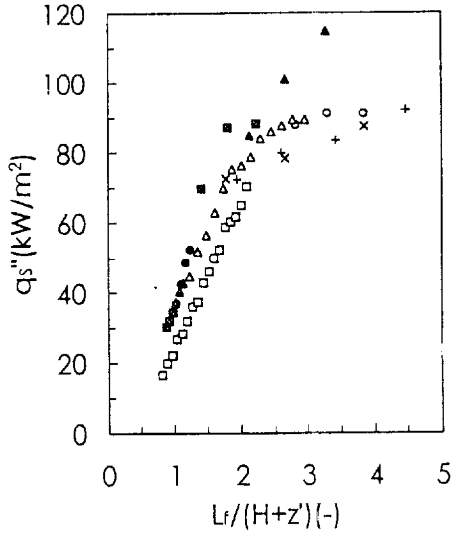


Figure 4 Stagnation Point Heat Flux Relation
Corrected with Virtual Heat Source

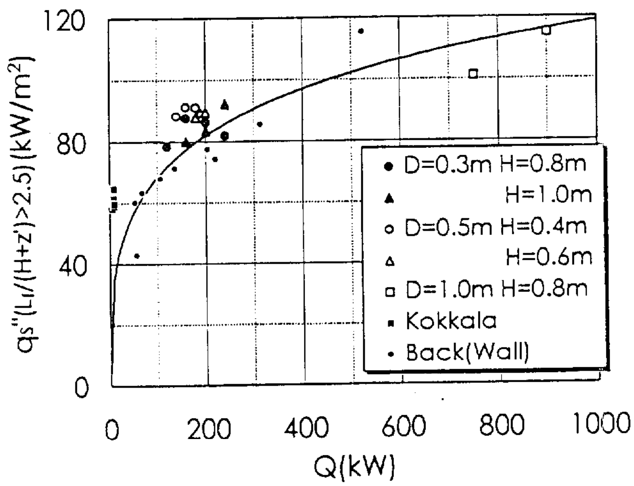


Figure 5 Plateau Heat Flux and Source Heat Output

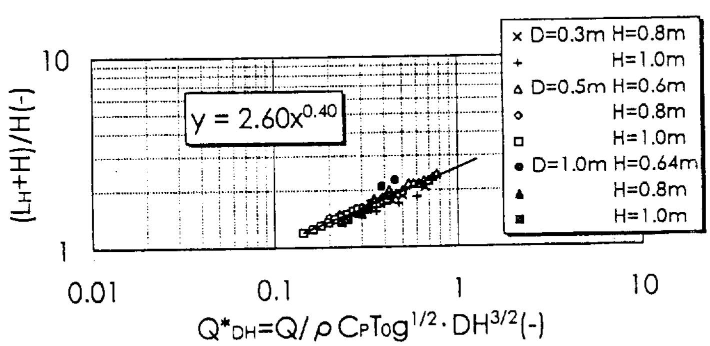


Figure 6 Flame Length Beneath Ceiling vs. Normalized Heat Release Rate

$$Q_{DH}^* = Q/\rho C_p T_o g^{1/2} D H^{3/2} \qquad (2)$$

as shown in Figure 6. Other dimensionless heat release rate, $Q_H^* = \rho C_p T_o g^{1/2} H^{5/2}$, was first examined to explain the flame length data as it had been reported that flame length data in room-corner configuration be correlated against Q_H^*[27] ; however, correlation of L_H against Q_H^* from the present test resulted in systematic difference between the 1.0m burner and others. Originally D^2 out of $D^{5/2}$ in the denominator of the dimensionless heat release rate, Q^*, indicates the jet-injection area, and full replacement of scale length in Q* by ceiling height is believed to miss the relevance of the dimensionless heat with Froude number. Figure 7 demonstrates relation between the heat flux to the ceiling and the radial distance from the stagnation point normalized by the flame length. The radial distance is corrected again with the virtual source concept. Almost all data are found to concentrate along one curve within relatively small range of scattering.

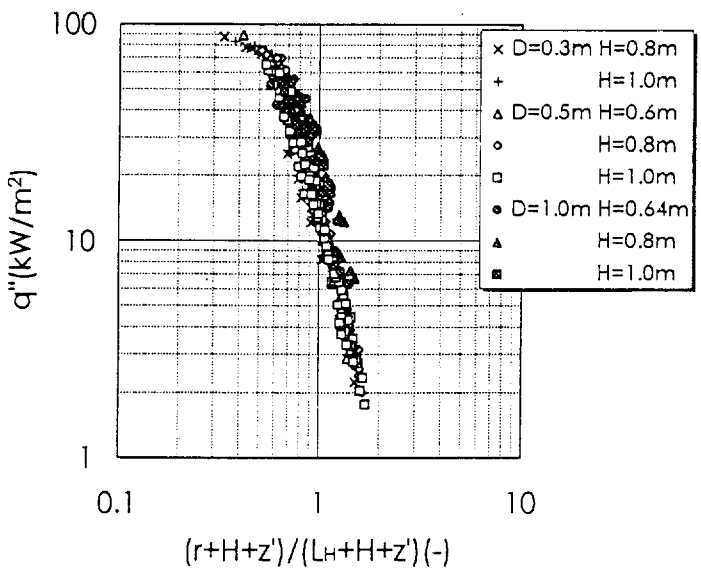


Figure 7 Radial Heat Flux Relation Corrected with Virtual Heat Source

BEAM AND CEILING EXPOSED TO A LOCALIZED FIRE SOURCE

Heating condition of steel beam installed beneath a ceiling slab exposed to a localized fire source has been measured using a 6 mm thick 75mm x 150mm x 3,600mm H-steel beam and a 1.82m x 3.64m rectangular flat ceiling(Figure 8). The cross-sectional size of the specimen could be interpreted as one fourth to half the typical load bearing steel beams in common buildings. The ceiling is composed of two layers of 12mm thick perlite boards. A 0.5m round and a 1.0m square porous propane burners were used as the fire source. Measurements were made on heat flux and temperature at the beam surfaces; heat flux gages were installed on the lower and upper flanges and the web through holes in the beam. Experimental conditions were chosen to cover the transient domain for the stagnation point heat flux, e.g. $1<L_f/H<2.5$, established for the flat ceiling configuration.

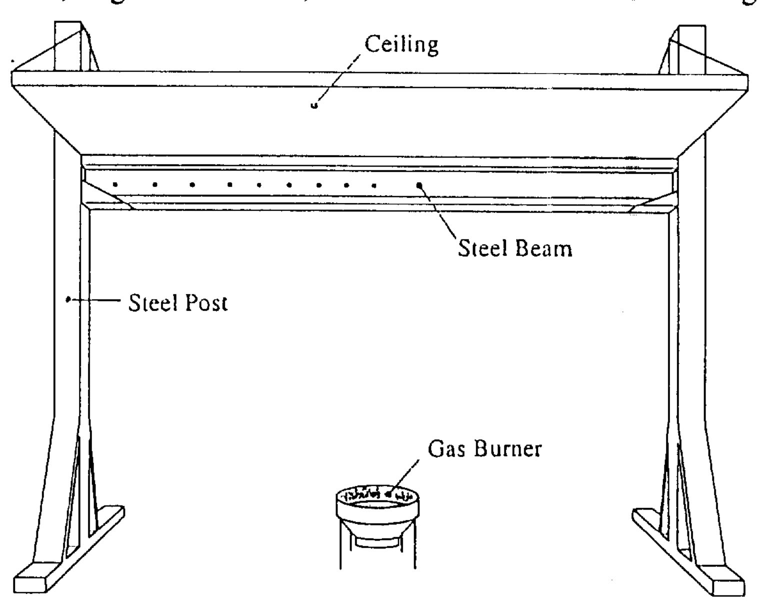


Figure 8 Experimental Setup(Ceiling+Beam)

General Test Result

Figure 9 shows an example of heat flux and surface temperature distributions along the beam at different cross-sectional locations. In the near field of the stagnation point, there is notable difference of heat flux in the vertical cross-section. This difference is more pronounced than its axial profile. Heat flux was generally weaker than the heat flux obtained at the flat-ceiling tests with the identical Lf/H condition. It is probably because of the flame flooding over the lower flange and separation of the flame to the both sides of the beam. Temperature field at each cross-section is more uniform than the heat flux field; it is probably a result of the high conductivity of the steel. Perhaps as result of this effect, temperature of the downward surface of the beam at the stagnation point was considerably lower than estimate from the heat flux at the same location based on the uniform heating, $(qs''/\varepsilon\sigma)^{1/4}$.

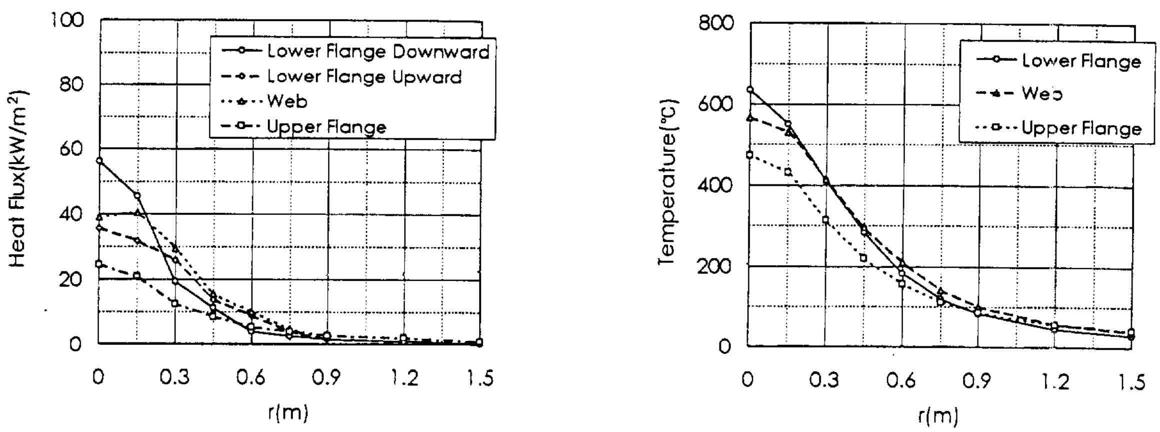


Figure 9 Heat Flux and Surface Temperature on H- Beam(HB=0.60m and Q=160kW)

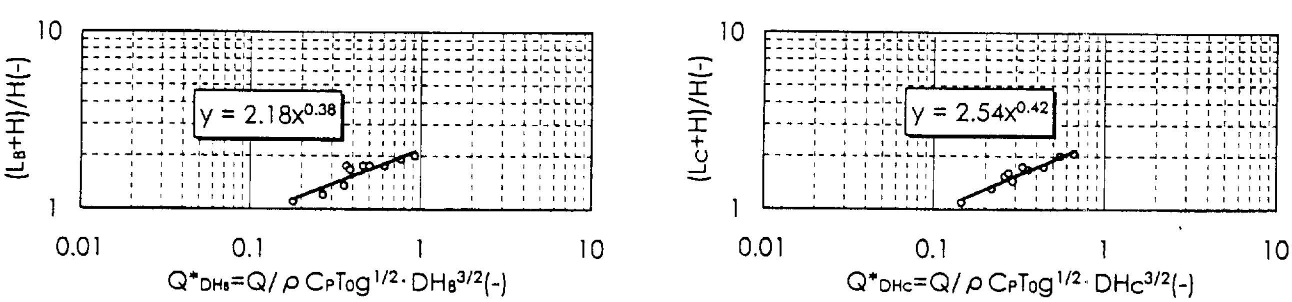
Flame Length

Local horizontal flame development was observed both beneath the ceiling and beneath the lower flange of the beam at each test; it seems that there is systematic difference between the two flame lengths. The flame lengths along the ceiling and along the lower flange of the beam are correlated against dimensionless heat release rates with ceiling height and with height to the lower flange respectively as Figure 10 where Q_{DHB}^* and Q_{DHC}^* are defined respectively as

$$Q_{DHB}^* = Q/\rho C_p T_o g^{1/2} D_{HB}^{3/2} \tag{3}$$

$$Q_{DHC}^* = Q/\rho C_p T_o g^{1/2} D_{HC}^{3/2}$$

The normalized flame lengths are nearly proportional to the 2/5 power of the dimensionless heat release rates for Q_{DHB}^* and Q_{DHC}^*.

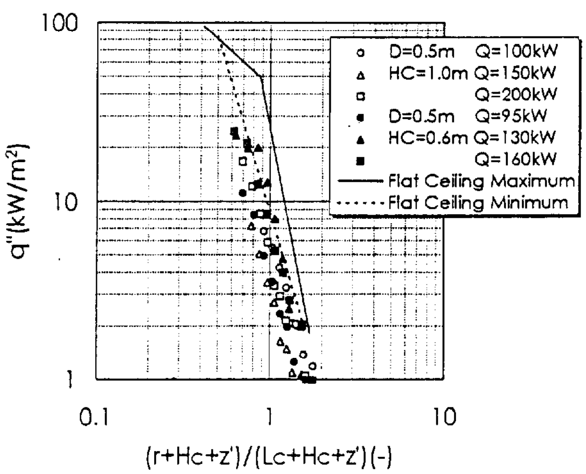


(a)below beam (b)below ceiling

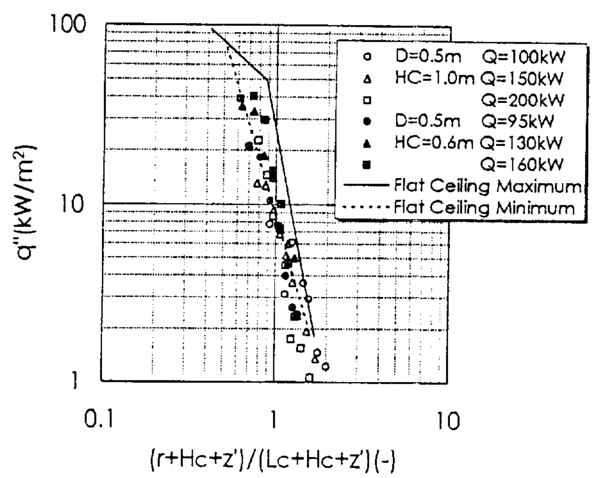
Figure 10 Flame Lengths below Beam and below Ceiling Supported by the Beam

Heat Flux Distribution

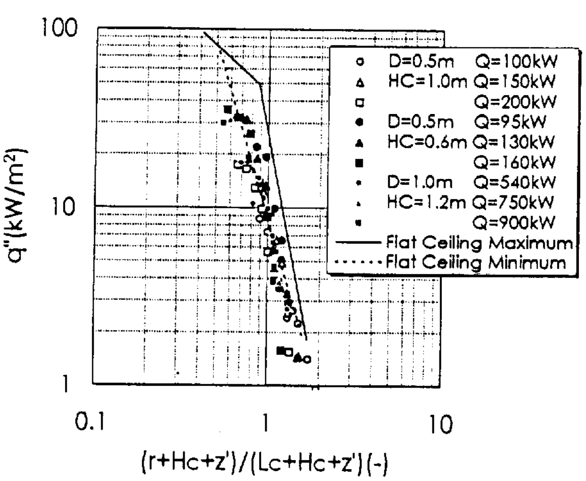
Heat flux data have been correlated against the heat source condition and geometry in a similar way with the flat ceiling tests. Figure 11 is a summary of the horizontal distribution of heat flux at the downward and upper surfaces of the lower flange, the web and the downward surface of the upper flange. The data for the downward lower flange surface were correlated against the flame length beneath the lower flange of the beam. Other data were correlated against the flame lengths beneath the ceiling. The decay of heat flux with horisontal distance for each crosssectional location seems to be faster than the data for the flat ceiling.



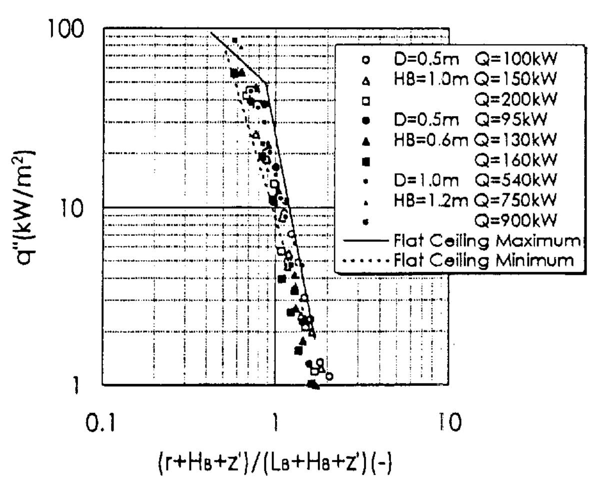
(a)upper flange downward



(b)web



(c)lower flange upward



(d)lower flange downward

Figure 11 Axial Distribution of Beam Surface Heat Flux

COMPARISON OF TEMPERATURE FIELD WITH NUMERICAL CALCULATION

Finite element calculation of the three dimensional temperature field within the beam has been conducted with the heat flux data as input. A general purpose finite element code ANSYS was used for the calculation. Considering the difference between the heat flux gage output and the net heat flux, convective surface heat transfer coefficient was estimated by comparing the temperature field of the flat ceiling between the test and calculation; hc= 0.01 kW/m^{2}K resulted in the best fit of the calculated ceiling temperature to the measurement. Figure 12 is an example of comparison between the present test and calculation on the upper-flange and lower flange temperatures.

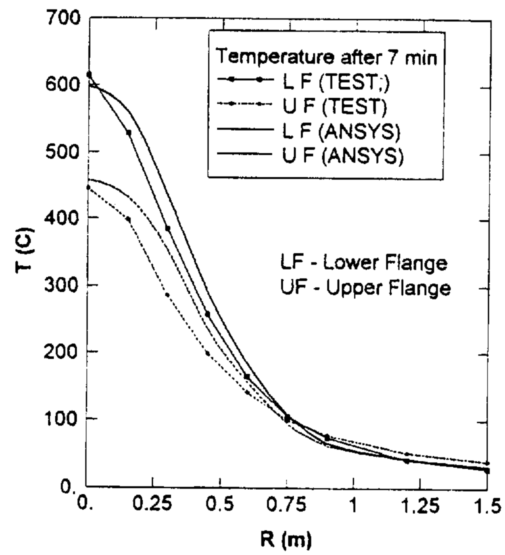


Figure 12 Comparison of Measured and Calculated Beam FlangeTemperature (Q=160kW, Hc=0.6m)

CONCLUSIONS

Measurements of flame heat transfer to a flat ceiling and to a beam supporting a flat ceiling by a localized fire have been made. The following conclusions can be drawn from the experiments.

(1) Horizontal heat flux distribution on a flat ceiling above a localized fire source can be represented as a function of the height of the ceiling and the horizontal length of the flame beneath the ceiling with correction based on the virtual source.

(2) Horizontal flame length beneath a flat ceiling becomes a function of heat release rate normalized with the ceiling height and fire-source diameter as the characteristic scale-length.

(3) Heat flux at the stagnation point of the ceiling surface shows significant transiency until Lf/H=2.5. The heat flux for greater Lf/H is almost constant within approximately the range of 80 - 120 kW/m^2 and seems to be an increasing function of heat release rate.

(4) Heat flux to a beam beneath a flat ceiling at the stagnation point is considerably smaller than the heat flux to a flat ceiling.

(5) Horizontal heat flux distribution along a H- beam supporting a ceiling above a localized fire source can be represented as a function of the heights of the lower flange of the beam and ceiling and the horizontal length of the flame beneath the ceiling with correction based on the virtual source.

(6) Temperature field within a beam exposed to a localized fire can be reproduced by finite element method with the heat flux correlation obtained from this study.

The horizontal flame length correlations with new characteristic lengths derived in this work should perhaps be considered still temporary, and it is doubtful if the correlations be as universal as the unconfined flame length relation as equation(1). However, it should be emphasized that the present tests cover the range of L_f/H for which consideration of the localized fire source scenario seems to have the most benefit for the structural fire safety design.

ACKNOWLEDGMENTS

The authors wish to thank Messrs.T.Nakazato and S.Nakagawa of the Kozai(Steel) Club for the arrangement of the specimen. The authors are also indebted to Messrs.T.Namba, E.Onoda, A.Inoue and T.Wakabayashi, students of the Science University of Tokyo, for the assistance in the experiments and for the preparation of drawings. A.V.Ptchelintsev was an STA Fellow(1994-1995) at Building Research Institute and a guest scientist at the Science University of Tokyo(1995).

TERMINOLOGY

Cp: specific heat of air, D: characteristic fuel size(e.g. diameter), H: height from fire source, H_B: height of lower flange beam from fire source, H_C: height of ceiling from fire source, L_f: unconfined flame height(flametips), L_H: radial length of flametips from the stagnation point of ceiling, Q: heat release rate, Q*: dimensionless heat release rate($Q/rC_pT_og^{1/2}D^{5/2}$), Q_{DH}*:$Q/rC_pT_og^{1/2}DH^{3/2}$, Q_H*: $Q/rC_pT_og^{1/2}H^{5/2}$, T_g: temperature of the sensitive part of a heat flux gage, T_o:ambient temperature, T_s: surface temperature of specimen, g: gravitational acceleration, h: total surface heat transfer coefficient, q": heat flux, qs":heat flux at the stagnation point, z: height from heat source, z': location of virtual source, ε : emmissivity, θ m: maximum excess temperature, ρ : density of ambient air, σ : Stefan-Boltzman Constant.

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Discussion

Gunnar Heskestad: I was very intrigued by the picture you showed of the flames underneath the I-beam and with the flame pattern under the bed, and the flame pattern under the ceiling. I wouldn't have guessed that and I've never seen it. Could you just describe that a little bit more?

Yuji Hasemi: Yes, that is based on the picture. But this is a very short time, I don't know how short it was. But if you have a long shut off speed, there's not any such cavity. So it is only because the drawing is based on the very short picture. From a scientific point of view, I am very curious.

Craig Beyler: I wonder if you could put up the first slide you were just talking to a moment ago. There was some work that was done at the Fire Research Station. He was doing a corridor experiment and was measuring heat fluxes to the ceiling. His went up in much the same way your data did. My recollection is that it went up 100 kW/m^2 and instead of having a simple plateau, it eventually came back down on the right part of the plot. Do you think that phenomenon might occur in your kind of experiment?

Yuji Hasemi: Yes, I tried to compare our results with other previous work. I think it may not be correct to say that it is a plateau because there may be some decay.

Craig Beyler: I wonder if I could ask a practical question. A rule of thumb that we often use in practice in terms of exposure of unprotected steel is based on the flame tip being about 500 °C and the critical temperature for steel failure being about 500 to 600 °C. The rule of thumb is that if you have flame contact, you will probably have a failure. Do your experiments have anything specific to say about that rule of thumb?

Yuji Hasemi: I considered that. We also measure the temperature over the beam. According to our measurement, the temperature was much lower always than the estimation. That is probably because of the high conductivity of the materials.

John Rockett: In a number of experiment of flames under ceilings that I have looked at, where the flame turns to extend out onto the ceiling, it already has entrained enough oxygen to burn all of the fuel present. This was true of Gross's data recently, and way back, Hinkley stated where they nearly had enough fuel so that the flame length under the ceiling would be determined by the ability to contain air in the horizontal ceiling jet. For analysis of fires, for example, some vehicle fires in tunnels, we desperately need data for fuel rich ceiling jets. Have you plans for experiments to those cases?

Yuji Hasemi: I should say yes. I am doing another project, and I think we can get some information from those experiments.